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An accurate optical method for the measurement of contact angle and interface shape of evaporative thin liquids films

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ABSTRACT

The aim of this study was to present an original method to compute the shape of the interface in the vicinity of the contact line after liquid film breakup. The liquid film is a controlled volume of evaporating liquid (HFE7100) filling a millimetric cylindrical vertical well. During the evaporation process, the liquid-gas interface takes on a toroidal shape delimiting an axisymmetric liquid meniscus (together with the well bottom and side walls). The first step of the evaporation process occurs without a contact line on the bottom and is followed, in the second step, by the creation and growth of a dry patch delimited by a circular contact line on the well bottom. The shape of the meniscus interface and the position of the contact line are instantaneously measured by laser sheet sounding from below and numerical inversion. This technique determines the variation of the light intensity of a laser sheet due to its refraction through consecutive interfaces (solid-liquid-vapor).The intensity of the laser sheet impact on a perpendicular screen is inverted. The inversion results provide the shape of the interface and the position of the contact line during the evaporation process. By this new method contact angles between 2 and 40 degrees can be measured and the interface shape can be obtained with high accuracy. This method is specially adapted for concave shape, as meniscus, where side view is not possible. It is perfectly complementary with the other classical methods (e.g., interferometry and goniometry).

1. Introduction

In the case of a drop or a thin film, the contact line is a geometrical and physical discontinuity that corresponds to a line in contact with the solid, liquid and gas. Heat transfer and fluid flow mechanisms in the vicinity of the contact line during evaporation and boiling process have been extensively researched since the early 1970s. Indeed, a better understanding of the (mass, momentum and energy) transfer in the vicinity of the contact line can lead to the development of technologies improving the control and the intensity of the heat and mass transfer a the contact line. The development of those technologies may help to improve the efficiency of high density heat exchanger. Lots of theory has been developed to represent the physic in the vicinity of the contact line. Nevertheless, theses theories depends of the geometry of the interface in the vicinity of the contact line. Lots of methods have been developed to measure the interface and the contact angle of drop as describe below. In case of meniscus, the interface shape is concave, this aspect turns more difficult the application of the classical method due to the lack of a side view, specially when the solid that contains the thin film is opaque.

1.1. Prior work

Many studies have demonstrated the influence of the contact line velocity, contact angle and film thickness on the heat and mass transfer at the contact line. Several techniques are available to measure the shape of the dynamic interface between of drop, meniscus or surface. Recently, Chau [1] published a review of the techniques available to determine the drop shape. He summarizes the measurement techniques for plates and categorizes them. The drop profile technique consists of the direct measurement of the contact angle by viewing the drop profile. Firstly developed by Bigelow et al. [2] who used a telescope goniometer approach this technique has been considerably improved with the used of a CCD camera. Hunter [3] showed that for contact angles greater than 20 degrees, an accuracy of 2 degrees can be obtained. The drop dimensions methods consists of measuring the curvature radius based on a photograph of the drop, where the entire profile of an axially symmetrical drop can be determining starting with the Laplace equation to describe the shape of the fluid interface. Fisher [4] described the relationship between the contact angle, radius, and volume in order to measure small contact angles. The limits of this method are noted when the shape of the drop is strongly influenced by gravity. An improved

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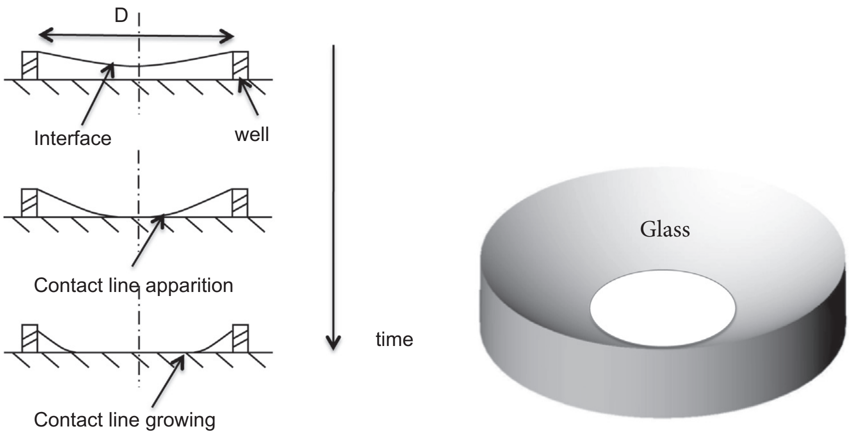

(a) 2 view of the evaporating liquid film

(b) 3D view of the liquid film with the central dry patch delimited by the contact line

Fig. 1. Toroidal film evaporation in a millimetrical well.

approach to this method is the axisymmetric drop shape analysis-profile method (ADSA-P). This technique was firstly developed by Rotenberg [5] and later improved by Spelt [6] and Cheng [7] It consists of finding the theoretical profile based on the Laplace equation that best matches the drop profile extracted from an image of the real drop, from which the surface tension, contact angle, drop volume, and surface area can be computed. Del Rio [8] reported that the ADSA-P method is more reliable and less sensitive to surface heterogeneity and/or roughness than the older techniques and therefore more suitable for mineral surfaces. Rodriguez-Valverde (2002) [9] reported that the captive-bubble method in conjunction with the ADSA-P technique allows easy-to-perform, automated and reproducible measurements of the contact angle on porous stones. In summary, this type of method provides good results for contact angles of greater than 20 degrees but a side view of the interface is required. Considering the widely spread small volume of liquids (thin films, drops or menisci), good accuracy is obtained by analyzing interferometry images (liquid wedge fringes), as reported by Scheid [20], Wayner [12] and Panchamgam [13], but this method is classically applicable to small contact angles. Nevertheless, recently Antao (2016) [21], developed an interferometry technique to measure contact angles around 50 degrees. Hegseth [14] developed an indirect optical technique which consists of observing the deformation of a projected grid due to the presence of a curved gas-liquide interface. This technique computes the interface shape of the film interface and the apparent contact angle. Other indirect methods have been developed using laser reflection and refraction. Allain [15] proposed a method that consists of illuminating the drop at a normal incident to the solid with a large laser beam. The beam is reflected by the drop into a light cone, and the angle is a function of the mean contact angle around the perimeter. Later, several other methods using laser were developed to determine the interface shape and contact angle. Light absorption techniques have been used by Goodwin [16]. Johnson [17] presented a fluorescent imaging system for the global measurement of liquid film thickness and dynamic contact angle in free surface flows. In an another method applied by Buguin [18] to axisymmetric dewetting, a laser beam is deflected by the interface and its deviation is followed versus time during the liquid dewetting. A similar technique using a laser sheet has been developed by Rio [19]. In this approach, the deflection of the sheet after its refraction across the liquid-vapor interface is used to determine the contact angle at the contact line of a dry patch. The measurement method describe herein is also based on the light refraction across the liquid-vapor interface. This paper demonstrates the ability of our method to instantaneously determine not only the contact angle but also the shape of the interface of an evaporative concave axisymmetric film.

1.2. Axisymmetric film evaporation problem

To illustrate the performance of the method, it was applied to an axisymmetric film configuration. This film appears during the evaporation process which occurs in a cylindrical well. A controlled volume of highly evaporative liquid (HFE_{7100}) is deposited in a millimetric cylindrical vertical well (Fig. 1). During the evaporation process, the liquid-gas interface takes on toroidal shape delimiting an axisymmetric film. Initially, the evaporation process occurs with no contact line on the bottom, the interface is dug on the center. A circular contact line then appears in the middle of the bottom of the film, delimiting a dry circular patch and subsequently this dry patch beings to grow.

This experiment provides important informations on the mechanism involved in the contact line: The contact line length in the middle of the bottom increases when the liquid-gas interface area decreases during the evaporation process. Thus, while evaporation is going on, the influence of the contact line on the transfer increases as the influence of the liquid gaz interface on the transfer decreases. Those influence temporal variations being opposite, they can be useful to highlight the effect of the contact line on the heat and mass transfer. Some results are straightforward in a future paper. But for this, a method that compute the shape of the interface is essential. This paper focus on the description of the method.

2. Material and method

2.1. Experimental set-up

The 6 mm inner diameter cylindrical well comprised of a 1 mm thick ring with a rectangular cross-section (Teflon) placed on a 1.1 mm thick glass blade was used in this experiment. This well was filled with a controlled volume of low boiling temperature fluid (HFE 7100). A laser diode ($\lambda = 635$ nm) was used to generate triangular laser sheets with a 30° opening angle. The laser sheets are reflected on a mirror to illuminate the glass blade from underneath and then refracted across the sides of the blade and the liquid vapor interface, impacting the screen positioned at around 15 cm above the glass plate. A high resolution (2848x4288) CCD camera is used to capture pictures of the screen at a frequency of 1 Hz and measures, spatially, the light intensity of the refracted laser sheet on the screen from the pixel value. The whole evaporation cell (glass blade, ring and liquid) is lifted by the plate of a high precision (10^{-4} g) balance which provides the liquid weight every second. This setup is shown in Fig. 2(a) and 3.